2.0 INTRODUCTION

The subject of this report involves the explosive demolition of concrete inside four steel-lined caissons. The objective of modeling the demolition is to relate the detonation of charges inside each caisson to the resulting acoustic pressure waves. Potential impacts of the acoustic pressure waves on marine wildlife can then be assessed based on the modeled acoustic estimates. The estimates are provided at discrete locations, as needed, so that safe ranges for marine wildlife can be determined.

The report includes a general description of the physical environment of the project site, the approach to modeling, the results, and the conclusions. A list of the references that were consulted is included, together with a glossary and another appendix describing the conversion tables used in the model, the scaling equations, and the basis for the refraction and diffraction calculations. Dr. Niels Winsor, an acoustic physicist with the Marine Mammal Consulting Group, Inc., based in Santa Barbara, California, performed the model calculations.

The basic components through which the acoustic waves will travel include the combustion products of the explosive, concrete, sand, metal, and seafloor sediments. An assessment of the transport through all the different materials that surround the explosion site was made so that the propagation of pressure waves which carry acoustic energy to other locations could be studied.

At selected ranges in three directions, predictions were made of the sound pressure level (SPL), impulse (Imp) and sound energy level (SEL) of the acoustic waves. SPL values are presented as decibels referred to 1 micropascal (dB re 1 μPa). Impulse values are given in pounds per square inch-milliseconds (psi-ms). SEL values are shown as dB re 1 μPa^2-s (second). Threshold values of SPL, impulse and SEL used in similar past projects for determining safe ranges for marine wildlife were applied to the model. These values are explained in detail in this report. The threshold values applied to the model are as follows:

- 180 dB re 1 μPa
- 12 psi-ms
- 182 dB re 1 μPa^2-s

The model computations assume a specific array of charges and order of charge detonations in the caisson. This configuration was designed by J. Kenny (Demex, pers. comm. 2002) as a means of minimizing pressure waves from the detonations. Kenny is an explosives expert who has been involved in numerous offshore decommissioning projects, including Chevron's 4H project.

The demolition procedures applied to this model were developed by professionals with expertise in the use of explosives for decommissioning projects. The specific procedures were designed to minimize potential impacts of explosives on marine life, while still effectively performing the demolition work. The effectiveness of the application of the model predictions will depend upon the applicant's selection of contractors familiar with such procedures and upon the ability of such contractors to implement procedures described in this report and in the Environmental Impact Report

2.1 FACTORS IN MODELING

2.1.1 Caisson Structure

Schematically, each caisson is a metal cylinder filled with sand and concrete. Steel pipes extend through the concrete, along with a concrete-filled steel center column. (For details and engineering drawings of the caissons, please see the EIR.)

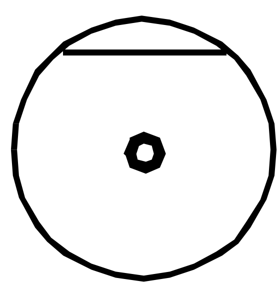
2.2.2 Caisson Demolition Strategy

The demolition strategy has many novel aspects, including cutting a door into one side of the caisson to provide a free face through which the demolished concrete can expand. It also includes cutting narrow vertical slits in the caisson wall around the perimeter. Small charges detonated in tight sequence will perform the demolition without simultaneously detonating too many charges, resulting in unacceptably high acoustic levels. Finally, a berm made from bags of gravel and sand will greatly attenuate sound pressure levels emanating from the door.

The process begins with a relatively small series of charges near the door. These start the demolition of the concrete. They also release a large amount of gas (combustion products), much of which will rise to the surface as a huge bubble. Some of the gas will be briefly trapped under the concrete slab, later to escape to the surface.

The slits in the caisson wall give the individual sections of wall the flexibility they need to avoid bursting due to the individual detonations. Therefore, these wall sections will reflect a large fraction of the acoustic energy back into the interior of the caisson, while the slits dampen internal acoustic modes, preventing high-amplitude reverberation.

Viewed from the top, a caisson with its door is shown in Figure 1 below.



←----27 feet----→

Figure 1. Top view of caisson
(Horizontal line is "door.")

The directions in which acoustic propagation were calculated are in front of the door, to the left and right, and opposite the door, all at the same level as the door. Distances were measured from the center of the caisson.

When detonations occur inside the caisson, the complex geometry will lead to interactions among direct and reflected waves. The resulting wave train was inspected for the peak pressure. In each direction, the expected peak pressure and impulse at selected ranges were estimated. The ranges at which the threshold values occur were then calculated.

2.1.3 Sound-Attenuating Berm

In the initial calculations, with no berm in front of the door, threshold values accepted by the regulatory agencies in similar past projects were reached at relatively short ranges (300 to 500 meters) to either side and behind the door. In front of the door, however, these values were initially reached at a range of one kilometer (1000 meters), which meant that a hazard zone of considerably more than 1000 meters (allowing for uncertainties in the model) would have been necessary for the protection of marine wildlife.

P. Howorth (MMCG, pers. comm. 2002), in consultation with Kenny (Demex, pers. comm. 2002) and T. Roche (Divecon Services LP, pers. comm. 2002), a commercial diving contractor, suggested building a berm in front of the door to reduce sound pressure levels coming out of the door. The size, configuration and composition of the berm was designed by Winsor to bring the sound levels out the door to levels comparable to levels in other directions. Facing the door toward any caissons that remain will also help attenuate sounds, but not to the extent provided by the berm. The configuration and composition of the berm were calculated by Winsor so that maximum sound attenuation could be achieved.

There are three essential requirements for configuring the berm. First, the side facing the caisson should be convex. It should be steeper near the bottom than it is near the top. Second, the top of the berm should be at least 2 meters (6.6 feet) higher than the top of the door. Third, it should be at least 1.5 meters (5 feet) wide near the top.

The calculations have assumed that the front edge of the top—the part which defines the profile as seen from the top of the door—is 5 meters (16.7 feet) away from the edge of the caisson. There is flexibility on this location, but the profile as viewed from the top of the door should remain at an angle of at least 20 degrees above the horizontal plane.

The berm should extend around the caisson as far as the edge of the door on both sides of the centerline. Preferably, it will be curved to stay at roughly a constant distance from the outside of the caisson. A straight berm with closest approach to the caisson at the center of the door will also work, or something between these two cases.

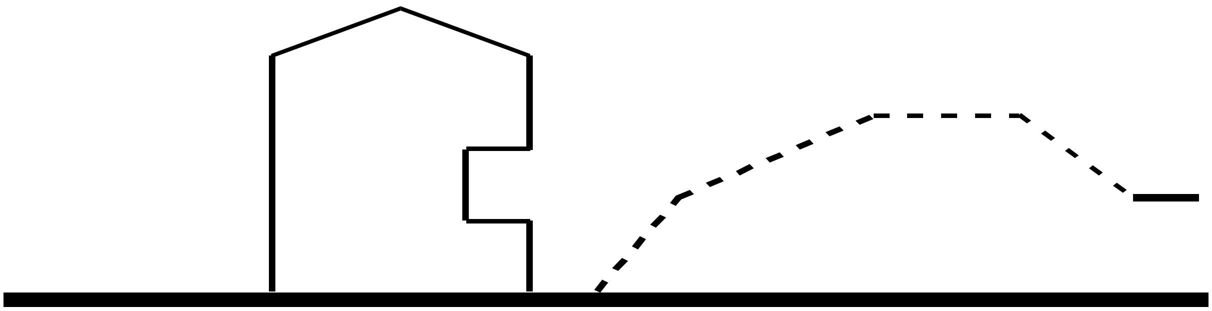


Figure 2. Profile of caisson and berm

Another essential element of the berm is that the material should be heterogeneous. Alternating bags of sand and gravel should be used to form the berm. There will be some sound transmission through the berm, and the more the local sound speed varies inside it, the more effectively it will scatter the sound that passes through it. For this reason, leaving some spaces between the bags for water will help further attenuate the sound.

2.1.4 Uncertainties in Estimates

Acoustic waves travel through most marine materials such as water, mud, sand, and rock. Many environmental influences affect the speed at which the waves travel. In water, the sound speed changes slightly as the temperature changes. Salinity also affects both the sound speed and the sound dissipation. In rock, many factors cause sound speeds to vary; among them, density, pressure (depth), presence of cracks, stress, and inclusions. In an environment containing more than one of these media, sound will travel with different speeds through different materials.

Why is this important? The answer can be understood in terms of an optical analogy. Light travels faster through air than it does through glass. Therefore, when light travels through specially shaped glass, such as a lens, it can either bend away from a region or focus into that region, depending on the shape of the lens. Similarly, the nature and shapes of geological strata can substantially reduce or increase the intensity of an acoustic wave.

For this reason, it is essential to the accurate estimation of the acoustic field that the nature and shape of the geological strata are accurately known between the source of the acoustic waves and the location of interest. Where these features are accurately known, the acoustic estimates can be calculated with reasonable accuracy. Where there are uncertainties in the geographic features, there will be corresponding uncertainties in the estimates.

In this case, the geometry is relatively simple. The caisson is on bedrock. Sound waves that enter the bottom material tend to be carried away from the region of interest—at the same depth of the caisson and above it—where marine creatures are. Furthermore, the bottom material resting on the bedrock is heterogeneous, so it tends to scatter the sound waves reaching it rather than focusing them.

2.1.5 Possible Anomalous Locations

The bathymetry of a given area of sea floor can sometimes result in a reflected or refracted and a nonreflected acoustic wave converging in phase at a specific location with a nonreflected wave, resulting in higher sound pressures farther from the source. This phenomenon occurred during the Mobil Seacliff Pier decommissioning project (Howorth 1998). For this project, reflection will occur inside the caisson itself, but the focus will be inside or near the caisson.

The location of the caissons directly on the bottom prevents refractive lensing. The sound, which is transmitted into the bedrock, travels a short distance inside the caisson, then expands through the shale at a speed more than twice the sound speed in water. Therefore, it quickly outruns the primary water wave, eliminating the possibility of simultaneous arrival at a location of concern for marine species (please see Section 3.1.4 for additional details).

2.2 BLAST PHYSICS AND NEED FOR MODELS

An explosive is a chemical compound or mixture that is capable of rapidly converting itself to gas when a detonator is applied to it. As a gas, its natural condition is to expand to a much larger volume at ambient pressure inside the caisson. While expanding, it pushes away anything in its path, such as rock, gravel, concrete, or even steel.

2.2.1 The Explosive Detonation

The details of an explosive detonation are very complex. The same amount of explosive, in different environments, can produce quite different acoustic signatures. The reason is that, when an explosive is in the process of detonating, the rate at which it converts itself into gas is proportional to the pressure. The higher the pressure, the faster the gas is produced.

The more tightly an explosive is confined in rock, concrete or steel, the higher the gas pressures the explosive will produce and the faster it will produce them. For this reason, the condition of the material being demolished by the explosive is very important. Weathered, cracked concrete will break up more easily, but it will also change the dynamics of the explosive detonation. For the purposes of modeling, the amount of energy released in each detonation, a typical rate at which it is released and the timing of different detonations are used to help determine threshold levels.

2.2.2 The Immediate Surroundings

Explosives are normally used to reduce a solid object such as concrete, to sand and small chunks of rubble. If the explosive is properly confined or has a very high detonation speed, then the solid material immediately surrounding it will be reduced to sand and dust. The pressure and temperature will be so high that concrete will be crushed. Some of this crushed material will be entrained in the gas product of the explosive. It will go with the gas, forming the cloud of dust frequently seen as the visual characteristic of the explosive event. In water, a large gas bubble bursts through the surface, carrying some entrained material and steam. This phenomenon was observed during several decommissioning projects in Southern California (Howorth 1996; 1997a and b; 1998). Some of the gas will be temporarily trapped under the concrete, creating a bubble curtain of sorts that will greatly attenuate and scatter sound coming out through the door as more charges are subsequently detonated.

Beyond the range at which the explosive can crush concrete, its gas products apply enough pressure to fracture the concrete. The fractures occur along weaknesses and irregularities. This phenomenon was observed during the demolition of several concrete caissons during the Mobil Seacliff Pier decommissioning project and was even photographed for those portions of the caissons that were out of the water (Howorth 1998). At still greater distances, the concrete is not broken, but transmits an acoustic wave through itself.

In parallel with the waves in the concrete, other acoustic waves are launched through the water, sand and through the gas from the detonation. All these acoustic waves reach the metal wall of the caisson. At that point, the acoustic levels depend very much what medium the wave is in when it arrives at the caisson wall.

The pressure of acoustic waves in water is mostly (90 percent) reflected from the metal wall. Much more of the wave energy coming through the concrete is transmitted to the metal. This difference is caused by the difference in the acoustic impedance (density times sound speed) of the concrete versus the water.

Once waves are in the metal of the caisson, only 10 percent of the wave energy is transmitted into the surrounding water, though more of it can be transmitted into the bottom sediments, assuming they have a higher acoustic impedance than water.

For these reasons, openings in the caisson, including the door cut in one side of it, are the main sources of acoustic wave transmission into the surrounding water. These openings are essential to the demolition process, however. Nonetheless, sound from the door, which produces the strongest acoustic wave, is greatly reduced by the berm discussed earlier.

3.0 BACKGROUND

The preceding discussion provided a detailed description of the processes that occur in an explosive detonation and the acoustic waves that arise from it. Following this chain of logic explains how events proceed from explosive detonation to a pressure wave at a specific location.

To present quantitative predictions of the SPLs and other quantitative measures anticipated at selected locations around specific explosive events, we need to define quantitative measures of pressure and impulse.

In an explosive detonation, the peak acoustic pressure varies over many orders of magnitude (multiples of ten) from near the explosion to miles away. For this reason a logarithmic scale expressed in dB is used. In such a system of measurement, when one pressure is ten times larger then a second pressure, the dB measure of the first pressure has a value that is 20 more than the second dB measure. That is, a multiplicative factor in the pressure in psi produces an additive term in the pressure in dB.

Impulse is a less familiar quantity. It is simply a pressure applied for a time; technically it is the integral of the pressure over time. In addition to peak pressure, impulse is a very important measure of the effect a pressure wave can have on a marine mammal. The pressure must be high enough to be able to do damage, but must also be applied *long* enough to actually *do* the damage. Therefore, both pressure and impulse are needed to determine whether a pressure wave can injure something exposed to it.

3.1 SPECIFIC MODELS

The behavior of the acoustic waves produced by an explosion is actually relatively easy to understand in qualitative terms.

Some energy that has been stored as chemical energy in the explosive is suddenly released. Initially, it occupies a volume slightly larger than the original explosive, then it rapidly expands to fill a much larger volume. The volume is proportional to the cube of its diameter, because it has three physical dimensions. For a sphere, the volume is $V = (4/3)\ \pi R^3$, where R is the radius of the sphere.

If the weight of the explosive is W, then the energy density within the sphere is proportional to W / R^3. This simple energy density relation appears almost universally among formulas for pressure and other quantities related to acoustic waves created by explosives.

There is a preference to express these relations relative to R to the first power, so the sub-expression which is usually seen is the cube root of the energy density divided by the radius, or $W^{1/3} / R$.

The important thing to remember that this is simply an expression related to the energy density in the volume that the explosive and the resulting acoustic waves have occupied.

3.1.1 Pressure in Ocean Water

In the absence of boundaries (water surface, bottom, rocks, etc.), low-amplitude pressure waves in water decrease their pressure linearly with the distance from the source. A high-amplitude acoustic wave, such as produced by an explosive, decreases its amplitude somewhat faster.

Pressure is a fundamental quantity because it determines whether a pressure wave has the ability to damage something. Similarly, a knowledge of the maximum pressure in a wave, at a specific location such as where marine wildlife is located, is a first criterion for whether the animals may be at risk from the pressure wave.

3.1.2 Impulse Scaling in Ocean Water

The second criterion that influences the safety of animals in surrounding water is called impulse. It is a measure of the pressure of the wave times the duration of that pressure. It decreases somewhat more slowly than linearly with distance from the explosive source of pressure.

3.1.3 Pulse Width Scaling in Ocean Water

One way that explosive pressure wave propagation is most unlike low amplitude pressure waves is in the behavior of the pulse width—the time duration of the pulse. A small wave in pure open water experiences almost no change in the pulse width.

The width of an explosive pulse increases with distance. It is not a particularly strong dependence, about the one-fifth power, but it has a very significant effect on the propagation of the wave over an obstacle such as the berm used to reduce sound pressure levels in this project.

3.1.4 Reflection, Refraction and Diffraction

Reflection is an important process in acoustic waves, which are reflected back down from the surface of the water as well as partially reflected by the seafloor and by rocks. The other part of their energy goes into a transmitted wave in the bottom or rock. At appreciable distances from the source, the water wave reflected from the surface tends to merge out of phase with the wave that has traveled directly from the source, helping to reduce sound pressure levels at greater distances.

This is the reason that the pressure in shallow water is lower near the surface. It would be especially significant if the explosives were detonated near the surface.

There is a special kind of reflection, called total reflection, which occurs at the boundary between a material with a lower sound speed and a material with a higher sound speed. This phenomenon can occur when pressure leaving the caisson from the bottom strikes the bedrock at an angle. At certain angles, all of the wave energy stays in the water. Most of that pressure wave energy will be reflected back into the caisson, however. The fraction of that energy which leaks under the caisson wall will propagate up through the berm outside the caisson and will be scattered by the berm.

Refraction is the term used when sound speed of the propagation medium changes, causing a change in the direction the wave is traveling. In ocean water, changes in salinity and temperature cause refraction. These effects are not important for the ranges of interest to us because the effects only become significant at ranges of tens of kilometers, which is far beyond the range at which safe threshold levels have already been reached.

Diffraction may seem to be a less familiar phenomenon, but it is easy to visualize in water surface waves. If a solid obstacle such as a breakwater is in the way of a large wave, the wave can be observed to bend around the end of the breakwater as it passes. Light does not appear to do this—it casts a shadow. The difference in these two behaviors depends on the wavelength of the wave compared to the size of the obstacle.

The key point is that diffraction removes energy and pressure from the wave when compared with an undiffracted wave. In a harbor with a breakwater, waves which get into the harbor come through a typically narrow opening between structures that reflect waves. When the waves come through the opening they then spread out, rapidly diminishing in strength, as if (which is actually the case) the source of the waves is the opening, not some distant event such as a powerful storm. In the absence of the breakwater, the waves would retain their strength.

Vertical diffraction is a very important phenomenon in the propagation of explosive waves in shallow water. When the wavelength of the pressure wave, determined by its pulse width, is a tenth or more of the depth of the water, diffraction of the acoustic wave in the water begins to bend parts of the wave toward the surface and bottom, resulting in a progressive reduction of the wave energy remaining in the water.

The water at the project site is too deep and the wavelength too short for this to be an issue, but diffraction does play a part in selecting the height of the berm in front of the door. Diffraction around the top of the berm determines the intensity of the forward wave beyond the berm.

3.1.5 Scattering and Absorption

Scattering and absorption are closely related physical phenomena. Both remove energy from a propagating wave. Both are of interest because they help to reduce acoustic levels to safe values or reduce the ranges at which they are dangerous to marine animals.

Two important processes that act to weaken a high-pressure wave are the presence of bubbles in the water and media with two sound speeds.

Bubbles have a dramatic effect on acoustic waves in water because the sound speed in the air inside the bubble is very much slower (600 m/s) than the sound speed in water (1500 m/s). In fact, under suitable conditions (Urick 1983), a volume fraction of only 0.01 *percent* of air bubbles in water can reduce the sound speed in the water to 53 percent of the speed in bubble-free water.

This means that a pressure wave traveling through a mixture of bubbles and water has different travel times along different paths. This destroys the coherence of the wave front and sends the energy in all directions, greatly attenuating the original wave.

Similarly, a medium, which consists of gravel and mud, has components (the gravel) in which the sound speed is typically 3000 to 5000 ms, while the sound speed in the mud is very close to that of water (Jensen 1994).

If there are systematic variations among either bubble clouds or gravel distribution in bottom mud, these regions can scatter or dissipate acoustic waves. This is why the heterogeneous composition of the berm is so important in attenuating sound.

There are many more scattering and absorption processes, but these are the most important.

3.2 DEPENDENCE ON LOCATION AND TERRAIN

Acoustic waves behave in an easily predicted fashion when they are deep in a material of known, constant physical properties. However, any inhomogeneity in the water, rock, mud, or soil through which the wave is propagating will introduce changes in the wave that can only be calculated from detailed knowledge of these features. Therefore, uncertainties in this analysis can only be removed by an impractically large number of additional measurements.

3.3 GENERAL FEATURES OF ANALYSIS

There are many uncertainties in the estimation of acoustic pressure waves resulting from an explosion. However, there is a large, well-developed set of analytical tools for treating each of the features of the propagation process. Many very powerful mathematical and analytical tools have been developed to calculate these quantities in very general conditions, such as acoustic propagation in inhomogeneous media. The computer has greatly refined and extended these tools.

The detailed structure of all the media in the path of the acoustic waves cannot be known for any practical demolition project. However, a reasonable number of core samples and logs containing acoustic data and other physical properties can provide statistical data on the expected acoustic transport properties. The modeling described below uses these approximations, and produces estimates of the expected SPLs at selected locations.

4.0 RESULTS

4.1 METHODOLOGY

The analysis of the acoustic pressure waves to be produced by the demolition of the caissons falls into two distinct parts. First, there is the complex interaction of the caisson and the demolition charges. This is the near field process, which requires analysis of the fluid dynamics of the exploding charges, the concrete and water inside the caisson, the caisson wall, and the water and seafloor material just outside the caisson.

Once the dynamics of the water and other material just outside the caisson are known, analytic propagation models are used to determine the pressure wave distribution much farther from the caisson. This is the far field calculation.

4.1.1 Near Field

The caisson geometry is approximated as an outer cylinder with a cylindrical core in its center. An elementary equation of state for the water inside it responds to the simultaneous discharge of a series of explosive charges inside it at the locations and times designated in the demolition plan.

4.1.1.1 Dynamics

The equations for the conservation of mass, momentum and energy are solved on a computational grid that overlays the caisson and a short distance outside it. Energy and momentum are transmitted to the caisson wall by both the water pressure and the concrete that is in contact with it.

The water pressure wave leaves the caisson to the front directly through the door. This is the most intense pressure wave caused by the detonations. This is like a set of charges, set in concrete, detonated in open water.

To the side, the pressure wave is a composite of that transmitted through the sides of the caisson and that which travels through the door and then expands to the side. It is less intense because the part of it which goes through the sides of the caisson is attenuated due to transmission losses through the caisson wall, and the part which comes from the door is attenuated by refraction and diffraction around the edge of the door. To the rear, most of the pressure wave arises from transmission through the caisson wall. Because of this, the weakest pressure wave would leave the caisson in this direction, if the berm were not blocking the direct wave from the door. The height of the berm is chosen to bring the levels beyond the door down to values similar to those in other directions.

4.1.1.2 Bubbles

There is a very noteworthy feature associated with this particular demolition geometry. The concrete which is being explosively demolished lies atop a bed of sand. When explosives are detonated in the concrete, the detonation generates a large quantity of gas, some of which forces its way below the concrete, displacing sand.

For a short time after that, this gas diffuses through the rubble created by the detonation, producing a bubble curtain of sorts between the remaining undemolished concrete and the door. This bubble curtain can greatly attenuate the pressure wave originating from the next set of charges, which are behind the bubble curtain when viewed from the door.

The result is that only the first set of charges couples directly to the water outside the caisson. Subsequent detonation pressure waves are scattered and attenuated by the bubble curtains created by previous detonations. (These explosively generated bubble curtains should not be confused with mechanical bubble curtains placed around detonation sites.)

4.1.2 Far Field

Once the pressure wave has left the caisson and become a pulse in the surrounding water, its behavior is well known. The subsequent propagation of the wave is described by analytic formulas. The changes in direction of the waves are caused by wave-mechanical processes.

Reflection, refraction and diffraction all play parts in the process. These are collectively called wave distortion effects in this case.

One of the more important is diffraction around the top of the berm. In the absence of diffraction, one could draw a line from the top of the door to the top of the berm, and expect the pressure wave leaving the door to cast a shadow beyond this path leading up to the surface. Because of diffraction, there is a reduced-intensity pressure wave propagating into this shadow zone. The geometry of the berm determines the amount of pressure-wave reduction observed at longer ranges from the caisson.

4.1.2.1 Scaling

The pressure, impulse and pulse width scalings are given in Appendix 2. At longer ranges (greater than 50 meters), their dependence on range is taken to be the distance from the center of the caisson. At shorter ranges, the distance from the location at which the match between the near field and the far field was performed is used.

4.1.2.2 Refraction

Inside and near the caisson, the fluid model handles refraction directly. Outside, it is treated using the acoustic impedance to calculate a refraction index, as discussed in Appendix 2. For the ranges of interest in this report, salinity and temperature gradients are not sufficient to affect the results.

4.1.2.3 Scattering

Based on the core samples obtained by de Wit (2001), the strata in which the caisson resides are highly inhomogeneous, so we expect the acoustic propagation in the bottom material to be scattered much more than the propagation in the water above it.

4.2 GEOMETRY

Computations of the near field acoustics were performed in the horizontal plane through the caisson, concrete and explosive charges. The structural elements include the core and wall of the caisson, the concrete slab, and the door in the wall.

These elements are illustrated in Figure 3, which is a view from 60 degrees to the left of the centerline through the door, and 30 degrees above the plane of the concrete.

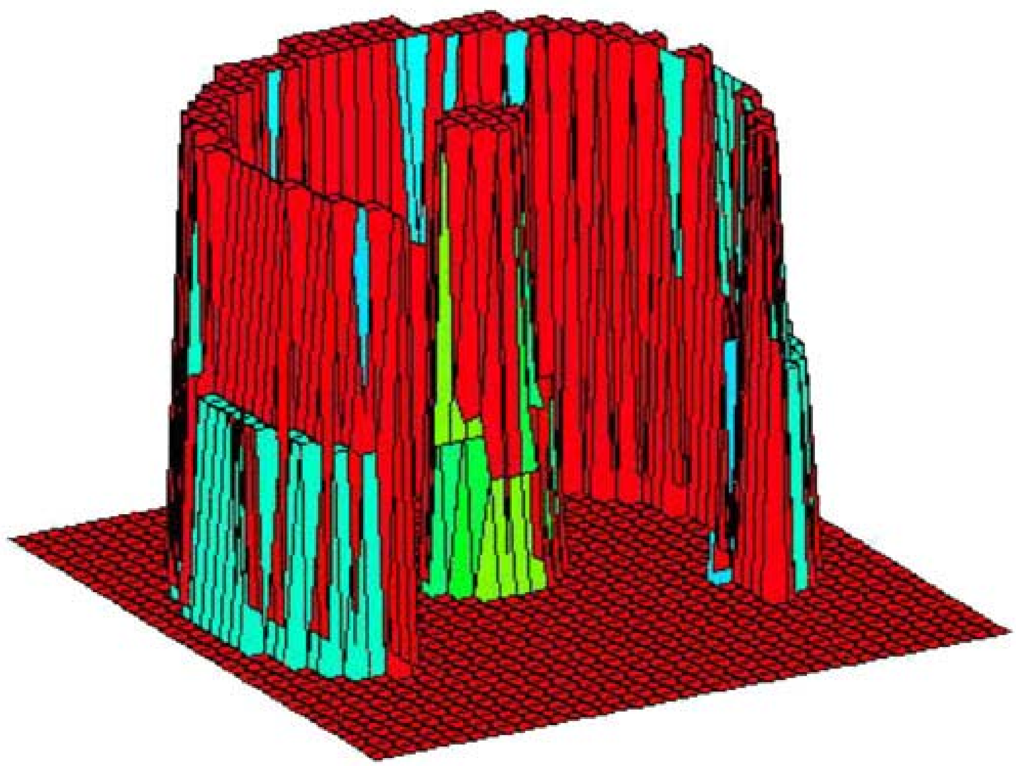


Figure 3. Geometry of a caisson

This shows the core in red above lime green, and the wall in red and cyan. The door is actually wider than it is high, but here it is depicted as a vertical cutaway.

The detonations take place in a regular pattern inside the caisson, with the rubble falling down or coming out through the door. In addition to breaking up the concrete, the detonations produce a large amount of gas. The composition of the gas will depend upon the explosive material that is ultimately used. That gas plays a valuable role in scattering the sound from subsequent detonations, significantly attenuating the sound from subsequent detonations.

4.3 NEAR FIELD RESULTS

The first detonations take place near the door. Figure 4 shows the pressure distribution shortly after the initial detonations. The pressure waves traveling inward, depicted in red and blue, have reached the core and the waves traveling outward, depicted in orange and green, provide a very intense pulse moving away from the caisson.

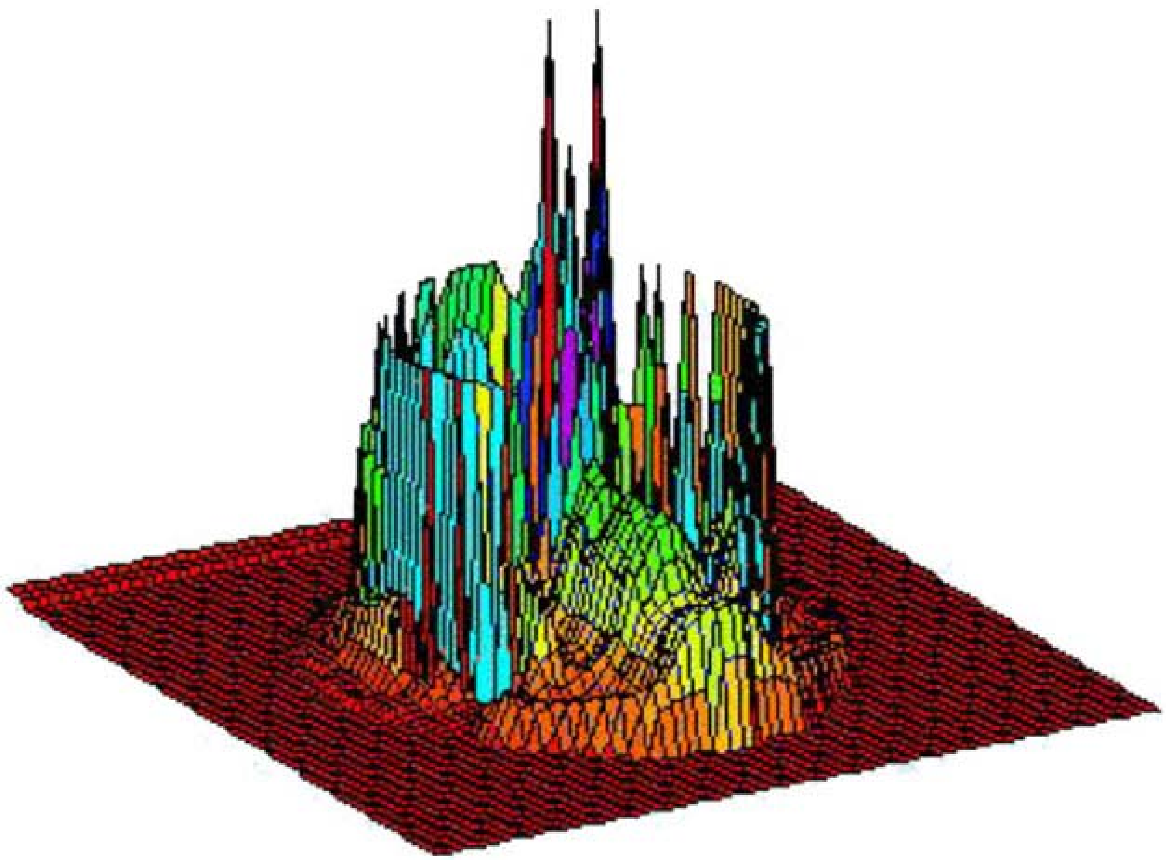


Figure 4. Pressure shortly after detonation

Here the geometry and perspective are the same as Figure 1, but the vertical direction is used to represent the amplitude of the pressure wave. Thus, the highest pressures are shown contained inside the caisson.

At this time, there is relatively little evidence of high pressure around the caisson away from the door. The caisson itself is containing the pressure waves traveling away from the door, and a very complex system of reflected waves is developing between the core and the wall of the caisson.

Figure 5 shows the conditions a few milliseconds later. The initial pressure pulse out the door has moved off the computational grid, and the reflections from the interior of the caisson, depicted in green and brown, are following after it.

Now an outward wave can be seen in brown all around the caisson, providing an explosive signature in all directions. Many high-amplitude reflections are still occurring inside the caisson, giving rise to additional components of the acoustic signal. These are depicted as part of the vertical column.

A close inspection reveals that the higher intensity acoustic waves are in front of, and to the side of, the door, while lower intensities are produced toward the rear.

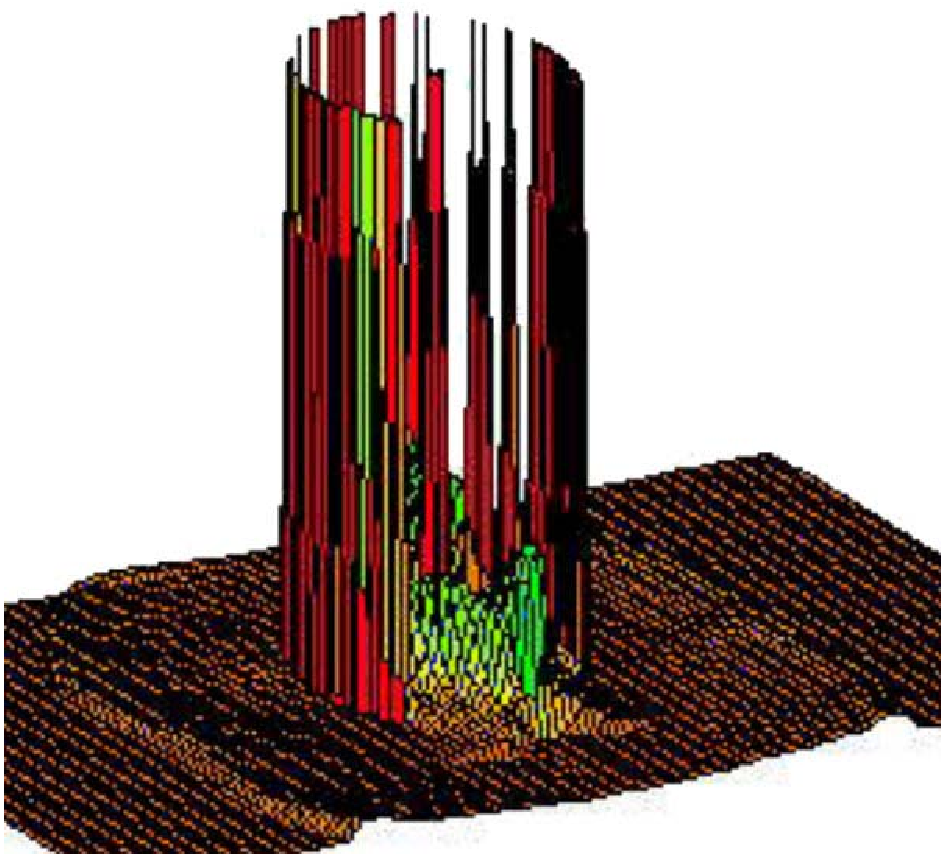


Figure 5. Wave outgoing in all directions

4.4 FAR FIELD RESULTS

Once the pressure wave has reached a distance of more than about 30 meters from the axis of the caisson, its behavior is predictable by methods used in open water.

In this far field region, the analysis begins with the pressure distribution calculated from the near field dynamics of the detonations inside the caisson. It then continues with the well-known dynamics of explosive-pressure wave propagation in water, modified by boundary effects such as diffraction. These are described in detail in Appendix 2 of this report.

Three quantities have been obtained to aid in the assessment of the potential for damage to marine life due to these pressure waves. These are the peak pressure, measured by the SPL of the wave, impulse and a closely related quantity, wave momentum.

Figure 6 presents the SPL as a function of the distance from the caisson axis. These pressures are calculated for the depth at which the explosives are set off, approximately 96 feet. The ranges at which the pressure levels of particular interest are predicted will be given in the next subsection.

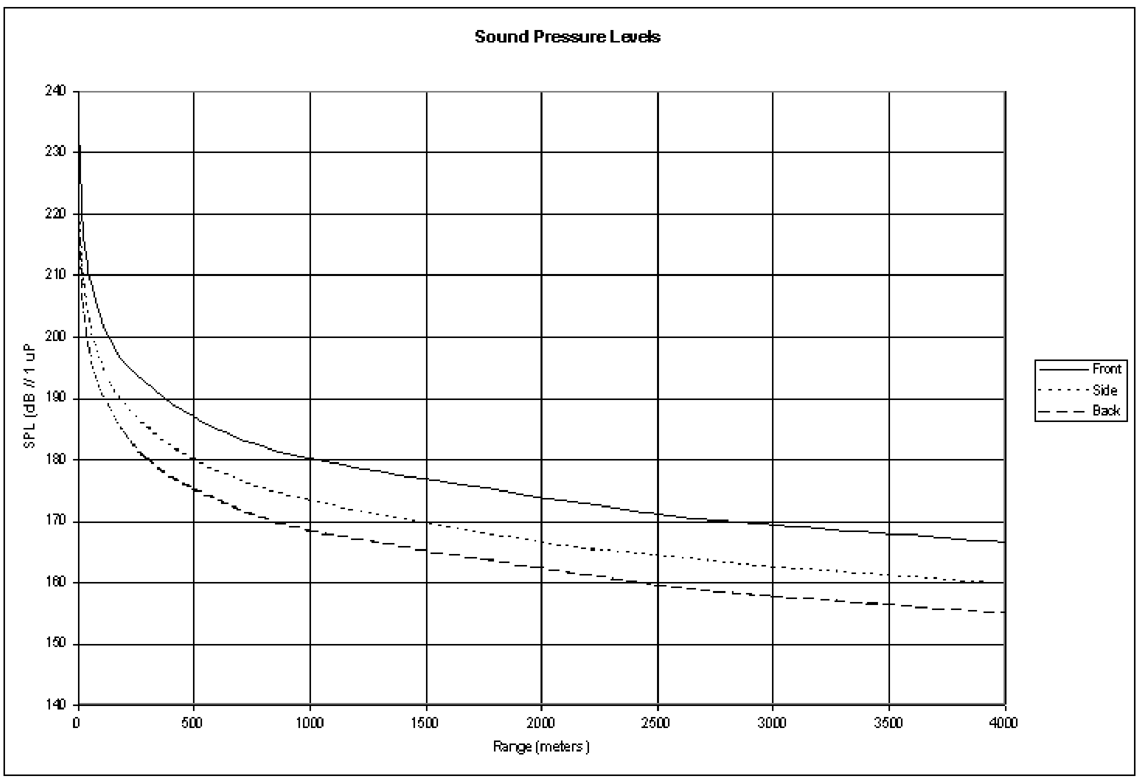


Figure 6. Sound pressure levels of the detonation

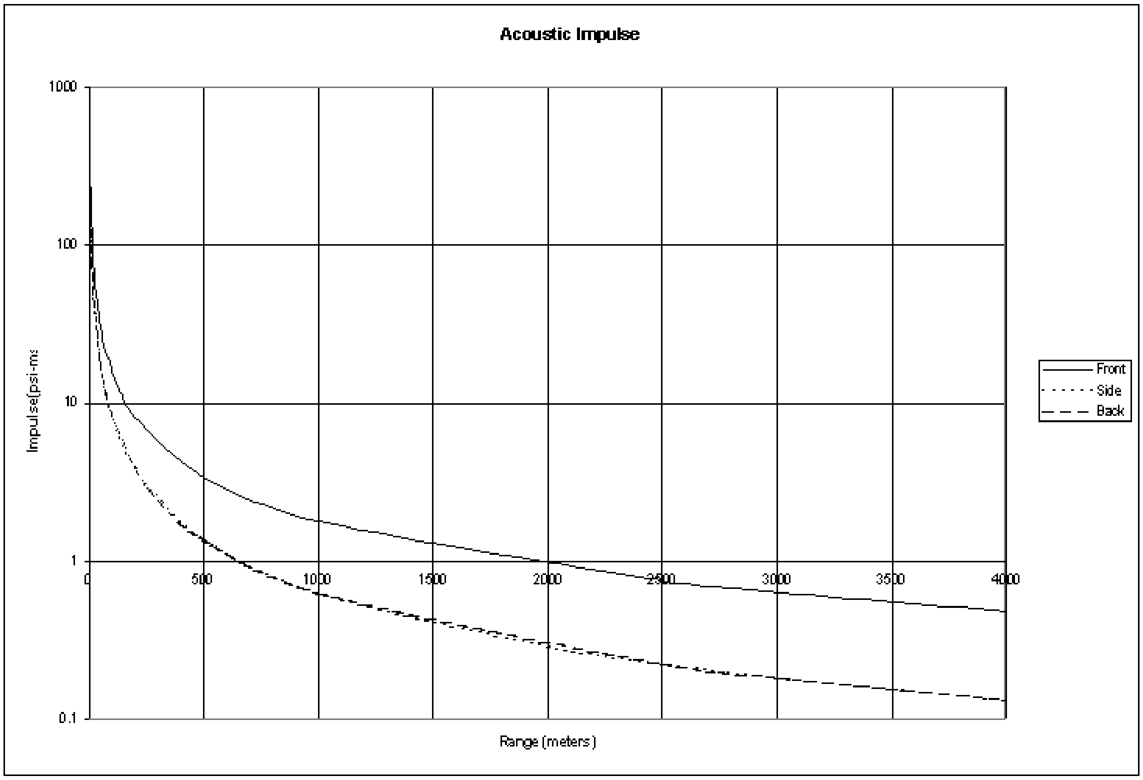


Figure 7. Impulse of the detonations

Impulse is defined as the integral of pressure with respect to time; that is, the average pressure (psi) in the pulse, times the duration (seconds) of the pulse. It has the dimensions of momentum per unit area.

Note in Figure 7 that the side and back impulse curves lie on top of each other. The SPL represents an energy flux, while the impulse represents a momentum flux. The metal of the caisson wall greatly attenuates the energy flux, while the momentum passes through with little attenuation. This is because of the physical boundary conditions which determine how energy and momentum pass through a boundary between dissimilar materials (concrete and metal, then metal and water).

Energy flux, measured by the pressure squared times the duration of the pulse, is also used as a measure of damage potential for acoustic waves. This is shown in Figure 8 on the next page. To calculate it, we have used the scaling of the pulse width from Appendix 2. In principle, the energy flux is comparable to the momentum flux in measuring the potential for damage from a pressure wave. In practice, it is something that is comparable to impulse only when all events occur in a homogeneous medium, such as open water.

When the acoustic wave propagates through different materials, such as concrete and metal, the acoustic impedance (ρc) changes. The energy flux calculated by this simple formula then changes by an often large factor. Therefore, we prefer impulse as a companion to the SPL in assessing the damage potential of an acoustic wave.

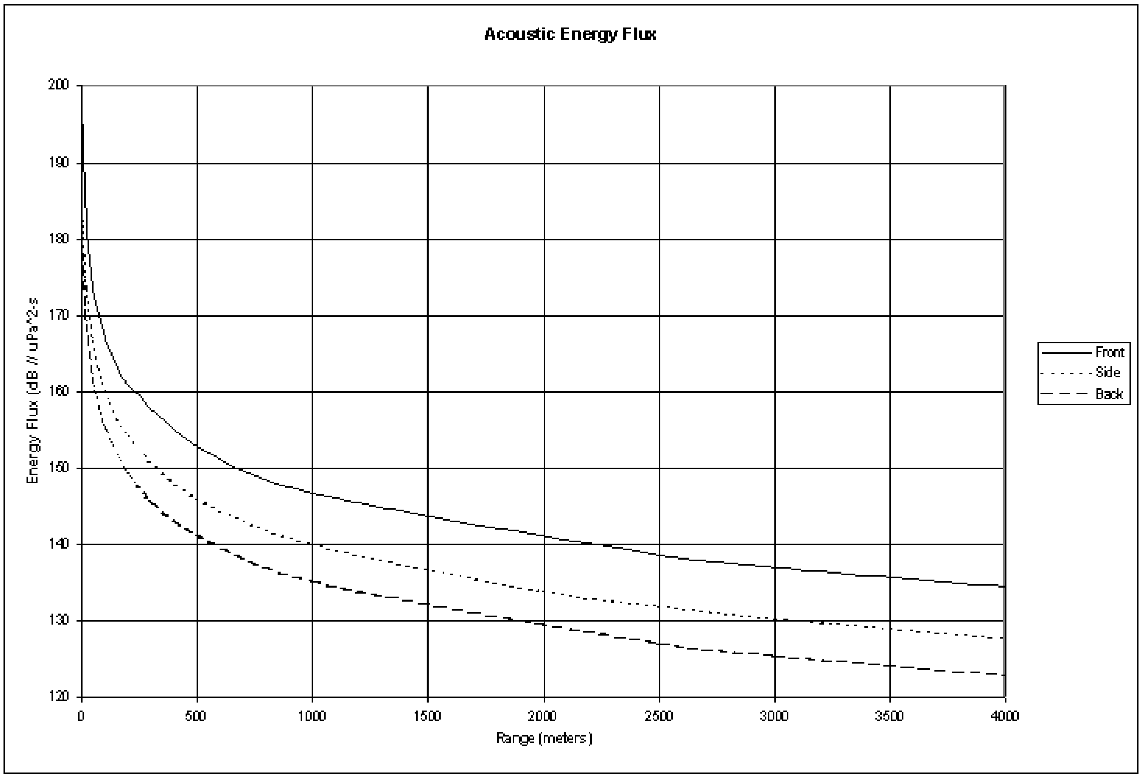


Figure 8. Energy flux of the detonations

4.5 DIFFRACTION

The preceding calculations are based on spherical spreading of the pressure waves. The result produces ranges of potential danger out to one kilometer, but only in the direction defined by the door in the caisson. As discussed earlier, the potential danger in this direction has been brought down to a range comparable with the other directions by placing the berm in front of the caisson.

For these calculations, it is assumed that the top of the berm is located five meters in front of the outer surface of the caisson, and the top of the berm is at an angle of 20 degrees above the horizontal plane when viewed from the top center of the door.

This berm casts an acoustic shadow in the pressure waves from the explosions inside the caisson. In the optical analogy, light waves from the door would pass above the berm. The region behind the berm, from which the door could not be seen, would be in total darkness.

The acoustic waves from the door have a much longer wavelength than light, so they can bend around the berm, and spread some sound into the shadow zone, but even the pressure which travels along the line of sight, just grazing the top of the berm, is reduced by 50 percent or by an attenuation factor of 0.5. This results in a reduction of acoustic intensity to 25 percent (SPL by 6 dB), compared to what it would have been in the absence of the berm.

Figure 9 on the following page quantifies this loss. In this figure, the diffraction angle of 0 degrees refers to the part of the pressure wave that travels straight along the line of sight and just grazes the top of the berm. The attenuation factor is 0.5, or 50 percent of the original pressure wave strength. The part of the pressure wave that is deepest in the "shadow" diffracts to an angle of 30 degrees and attenuates to less than 0.1.

The height of the berm has been chosen to bring the SPL in front of the door down below the SPLs predicted for other directions. This leaves some margin in case the force of the detonations displaces some material off the top of the berm.

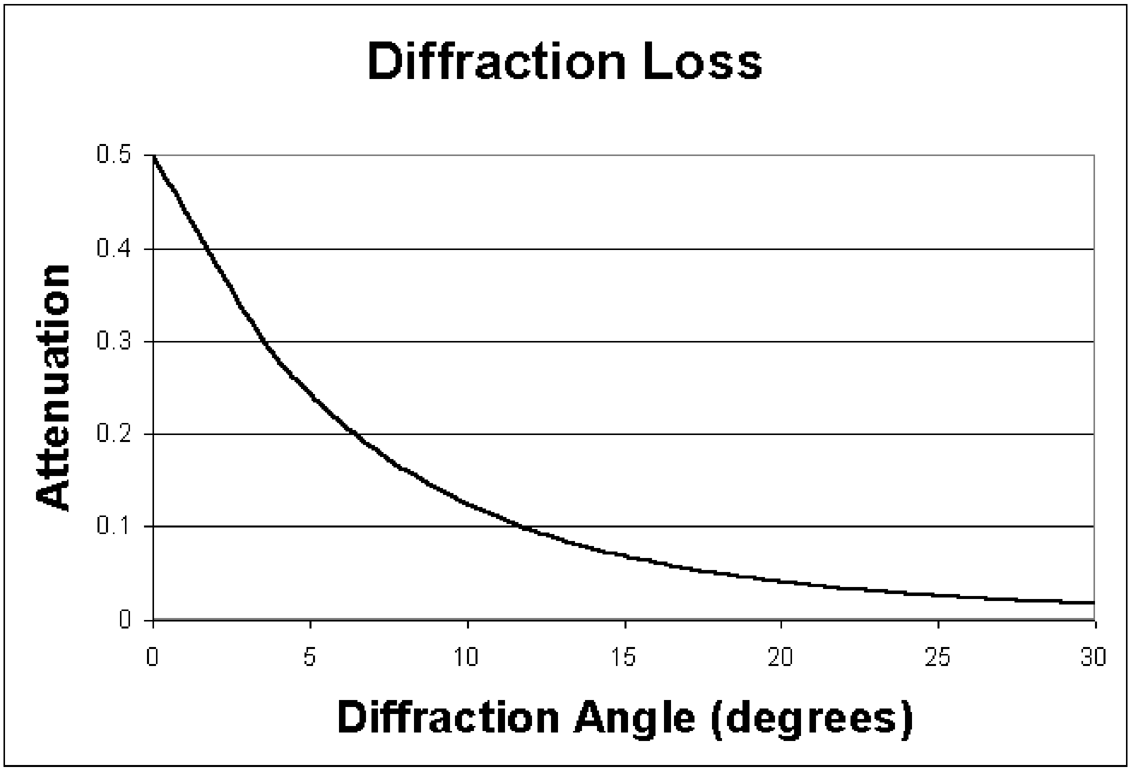


Figure 9. Acoustic attenuation due to diffraction behind berm

4.6 KEY RANGES

As mentioned earlier, the thresholds which have been accepted by the regulatory agencies as safe for marine mammals during similar projects are a SPL of 180 dB re 1 μPa; an impulse of 12 psi-ms; and a SEL of 182 dB re 1 μPa^2-s. The ranges at which these levels occur are used to establish hazard zones and safe zones for marine life.

This subsection gives the ranges at which these levels are predicted to occur, at the depth of the detonations (96 feet), and 2 meters (6.6 feet) below the surface. For completeness, each parameter is given at a range for which one of them passes a threshold.

The highest levels occur for the sound out the front (through the door) of the caisson, as depicted in Figure 3. As explained earlier, these levels will be greatly attenuated by the berm. Table 3 below shows at what ranges and directions the threshold levels are reached at the depth of the detonations.

Table 3. Key parameters at a depth of 96 feet and various ranges and directions

Direction	*Range (m)*	*SPL (dB re 1 μPa)*	*Imp (psi-ms)*	*SEL (dB re 1 μPa^2-s)*
front	20*	220	74	182
front	133*	200	12	165
front	230	180	1.8	147
side	13	220	130	182
side	75	200	12	163
side	500	180	1.4	146
back	11	218	187	180
back	75	194	12	158
back	300	180	2.5	146

*At depths above the geometric shadow cast by the berm on sound from the door

The far field calculations assume spherical spreading after wave distortion effects, so the acoustic levels near the surface can be calculated based on the slant distance from the outside of the caisson to the location of interest. Diffraction over the top of the berm reduces the levels in front of the door, far from the caisson.

Table 4. Key parameters at a depth of 6 feet and various ranges and directions.

Direction	*Range (m)*	*SPL(dB re 1 μPa)*	*Imp (psi-ms)*	*SEL(dB re 1 μPa^2-s)*
front	23*	217	62	180
front	63	200	12	165
front	280	180	0.3	145
side	23*	217	62	180
side	71	200	12	163
side	500	180	1.4	146
back	23*	217	62	180
back	71	194	12	158
back	299	180	2.5	146

* At the surface, over the caisson.

Waves traveling through the bottom material, even if they travel faster than in water, are carried away from the direct water waves. Furthermore, the explosive charge sizes and sequences provide a series of acoustic pulses, each with a short pulse length, so that at the level of the charges and above, the pulses are not long enough for waves in the bottom material to reach the water wave in time to constructively combine within the 200-meter range at which both the SPL and impulse are above their thresholds.

4.7 SUMMARY OF RESULTS

The objective of these computations is to calculate the important acoustic parameters associated with the demolition of the Hazel caissons. Their presentations are summarized by the ranges at depth and near the surface at which these parameters reach certain thresholds.

The following table summarizes the ranges at which the threshold levels are reached at the depth of the demolition activity.

Table 5. Summary of threshold ranges in meters at the depth of the demolition (96 feet)

Quantity	*SPL*	*Impulse*	*SEL*
Threshold Unit	180 dB re 1 μPa	12 psi-ms	182 dB re 1 μPa^2-s
Range (front)	230	133*	20*
Range (side)	500	75	13
Range (back)	300	75	11

*At depths above the geometric shadow cast by the berm on sound from the door

The next table summarizes the same information for 6 feet (1.8 meters) below the surface.

Table 6. Summary of threshold ranges in meters 6 feet below the surface.

Quantity	*SPL*	*Impulse*	*SEL*
Threshold Unit	180 dB re 1 μPa	12 psi-ms	182 dB re 1 μPa^2-s
Range (front)	280	63	N/A*
Range (side)	500	71	N/A*
Range (back)	299	71	N/A*

*Threshold occurs below this location.

5.0 CONCLUSIONS

5.1 RANGES

The acoustic pressure waves which the caisson demolition will create are highly directional. The highest amplitude waves are launched out the door, where the demolition sequence begins. These are muffled by the berm, however. At the depth of the detonations, the impulse and SEL emanating from the door drop below threshold within 133 meters. The SPL drops below threshold at a range of 230 meters. On the side (perpendicular to the direction out the door), the SPL drops below threshold at 500 meters, or about half the range at which thresholds were reached during the 4H decommissioning project. Toward the back—opposite the door—the SPL drops below threshold at about 300 meters.

Within six feet of the surface, the pressure waves are very similar from the sides and back. Out the door, the range at which the thresholds are reached is somewhat longer (280 meters) because of the depth of the water and diffraction.

5.2 GENERAL CONCLUSIONS

By themselves, the caissons do a good job of muffling the acoustic emissions of the demolition process. However the door, which is an essential part of the plan, lets out enough acoustic energy to reach significant source levels up to a kilometer from the caisson. The addition of the berm in front of the door will scatter and diffract the pressure waves enough to drastically reduce the SPLs in front of the door.

The calculations provide conservative estimates of the pressure, impulse and energy levels to be expected in the demolition process. These values should aid in determining safe distances for the protection of marine life.

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APPENDIX 1: GLOSSARY OF TERMS

acoustic impedance -- a characteristic parameter, ρc, of a fluid. Here ρ is the mass density and c is the small-signal sound speed. The acoustic impedance determines reflection and refraction characteristics at fluid interfaces and the relation between momentum and energy in the fluid.

dB -- a logarithmic measure of a measured quantity, relative to a reference value. The phrase "dB re 1 μPa," spoken "decibels relative to one micropascal" refers to the following operations: Divide the measured value by one micropascal. Take the logarithm to the base 10 of that ratio. Multiply the result by 20. For example, if a measurement is 2 pascals, then 2 Pa / 1 μPa is 2,000,000. The logarithm is 6.3 (rounded to the nearest 1/10), and the result is 126 dB re 1 μPa. [For reasons beyond the scope of this discussion, if the reference value is a power rather than a pressure, then the multiplier of the logarithm is 10 rather than 20. Historical evolution has created many inconsistencies in scientific notation.]

diffraction -- A process in wave motion that allows waves to "bend around corners." Waves with longer wavelengths bend farther around corners. This is why an explosion can be heard or felt where it cannot be seen.

heterogeneous – A medium made up of many different materials jumbled together. Especially one in which the sound speed varies significantly throughout different parts of a path through the medium.

homogeneous – A medium with uniform properties throughout. A medium which does not itself modify the behavior of a wave traveling through it.

impulse -- a measure of the ability of a transient wave to damage something in its way. Impulse has the dimensions of pressure times time. Measurement of impulse recognizes the fact that a very short pulse of high pressure may do less damage than a longer-duration pulse of the same pressure.

pascal -- a unit of pressure in metric (*Système International*) measurement. One atmosphere at sea level is approximately 100,000 pascals.

period -- the shortest time after which a wave repeats its behavior. Not applicable to impulsive waves such as explosion pressure waves.

pressure -- the property of a material that expresses its ability to deliver energy to its neighbors. Acoustic waves are measured by the pressure they transport through materials. When one material applies a pressure, P, to its neighbor, and the interface between them moves a distance, x, then the first material has transferred an amount of energy, Px per unit area, to the second material.

pulse length -- the amount of time a pulse is on. For an isolated pulse such as an explosive pressure wave, the start and end of the pulse are chosen as a certain percentage, such as 10 percent, of the maximum between them.

reflected wave -- the fraction of a wave incident on a material boundary that remains inside the original material. This fraction is determined by the acoustic impedances of the two materials and the angle between the direction the wave is traveling and the direction of the interface between the materials.

refraction -- a change in the direction of travel of waves due to inhomogeneities in the medium through which it is propagating. In ocean water, both temperature and salinity change with depth and location. These changes cause waves propagating through the region in which they are changing to change the direction of propagation.

source level (SL) -- measured in dB re 1 μPa @ 1 m and spoken "source level in decibels relative to one micropascal at one meter." The acoustic power of a source. This is the distance-independent measure of the loudness of an acoustic signal generator when observed from front and center. Typically, it is measured far away in deep water and reduced to a range of one meter by using 1/r scaling.

SPL -- sound pressure level, as used here, measured in dB re 1 μPa. Unfortunately, SPL has also been used for source pressure level, source power level and spectral power level.

total reflection – reflection of all the energy in a wave. This occurs beyond a certain angle of incidence when an acoustic wave is incident on a boundary between a fluid with a lower sound speed and one with a higher sound speed. The critical angle at which this begins is where the incident wave would be refracted into a wave whose direction would be exactly parallel to the boundary.

transmission loss (TL) -- measured in dB. The ratio of the source level to the received signal level. Since it is a ratio, the reference levels don't matter; they just have to be the same for both measurements.

transmitted wave -- when a wave impinges on a material interface, this is the part of the wave that propagates into the second material, caused by the original wave in the first material. The sum of the energies in the transmitted and reflected waves is equal to the energy in the original wave.

wavelength -- the speed of sound times twice the pulse width. (For sinusoidal waves, it is the sound speed times the period.) Waves propagating in a water depth shallower than the wavelength are subject to rapid energy loss. If the water is not much deeper than the wavelength, the waves are subject to less rapid energy loss due to diffraction.

APPENDIX 2:

2.1 CONVERSION TABLES

A number of quantities of interest are actually different representations of the same physical quantity. The most important example is the pressure. Pressure can be expressed in atmospheres (atm), pascals (Pa; the metric unit), or pounds per square inch (psi; the English unit).

Two other units with direct conversion to pressure are peak particle velocity (ppv) and SPL, though the conversion of ppv to pressure depends on the density and sound speed of the medium in which the measurement is being made. The two tables presented in this section give the ppv conversion for water.

Power is defined as force times velocity. On a per-unit-area basis, this is the relation among power flux, pressure and ppv. This means that the power, which is the pressure times the ppv, is proportional to the square of the pressure.

Power is what really can do damage. It is what is really being measured by SPLs. The amount of damage it can do is measured separately by impulse.

Table 7. Pressure conversions -- Large pressure intervals

N	SPL	Power flux	<----Pressure---->			Particle velocity
	dB	w/m^2	Atm	Pa	psi	cm/sec
1	300	6.667E+11	10000	1E+09	150000	66666.667
2	280	6.667E+09	1000	1E+08	15000	6666.6667
3	260	66666667	100	1E+07	1500	666.66667
4	240	666667	10	1000000	150	66.666667
5	220	6667	1	100000	15	6.6666667
6	200	67	0.1	10000	1.5	0.6666667
7	180	0.67	0.01	1000	0.15	0.0666667
8	160	0.0067	0.001	100	0.015	0.0066667
9	140	6.667E-05	1E-04	10	0.0015	0.0006667
10	120	6.667E-07	1E-05	1	0.00015	6.667E-05
11	100	6.667E-09	1E-06	0.1	1.5E-05	6.667E-06
12	80	6.667E-11	1E-07	0.01	1.5E-06	6.667E-07
13	60	6.667E-13	1E-08	0.001	1.5E-07	6.667E-08
14	40	6.667E-15	1E-09	1E-04	1.5E-08	6.667E-09
15	20	6.667E-17	1E-10	1E-05	1.5E-09	6.667E-10
16	0	6.667E-19	1E-11	1E-06	1.5E-10	6.667E-11

Table 8. Pressure conversions -- small pressure intervals

N	SPL	Pwr flux	<----Pressure---->			Particle velocity
	DB	w/m^2	Atm	Pa	psi	cm/sec
1	240	666667	10	1000000	150	66.666667
2	236	266667	6.32	632456	94.9	42.163702
3	233	133333	4.47	447214	67.1	29.81424
4	230	66667	3.16	316228	47.4	21.081851
5	226	26667	2	200000	30	13.333333
6	223	13333	1.414	141421	21.2	9.4280904
7	220	6667	1	100000	15	6.6666667
8	216	2667	0.632	63246	9.49	4.2163702
9	213	1333	0.447	44721	6.71	2.981424
10	210	667	0.316	31623	4.74	2.1081851
11	206	267	0.2	20000	3	1.3333333
12	203	133	0.1414	14142	2.12	0.942809
13	200	66.7	0.1	10000	1.5	0.6666667
14	196	26.7	0.0632	6325	0.949	0.421637
15	193	13.3	0.0447	4472	0.671	0.2981424
16	190	6.67	0.0316	3162	0.474	0.2108185
17	186	2.67	0.02	2000	0.3	0.1333333
18	183	1.33	0.01414	1414	0.2121	0.0942809
19	180	0.667	0.01	1000	0.15	0.0666667
20	176	0.267	0.0063246	632	0.0949	0.0421637
21	173	0.133	0.0044721	447	0.0671	0.0298142
22	170	0.0667	0.0031623	316	0.0474	0.0210819
23	166	0.0267	0.002	200	0.03	0.0133333
24	163	0.0133	0.0014142	141	0.0212	0.0094281
25	160	0.00667	0.001	100	0.015	0.0066667

Note that these tables apply only in water. Conversions are different in rock, air and other media. Note also that impulse does not appear in these tables. It is a fundamentally different quantity from pressure. While pressure (squared) represents power, impulse represents energy. Impulse is the product of the average pressure times the time it is applied.

2.2 SCALING EQUATIONS

There is a long history to the analysis of pressure propagation under water, particularly in ocean water. Arons (1954) first noted scaling laws which are still in use today. In fact, one of the reasons that explosive weights are measured in pounds, and ranges in feet may be because of the very widespread use of these formulas. [If you would prefer to have them in metric units, see Richardson *et al.* (1998).

The first, and most famous of these relations is the scaling of pressure with range and charge weight. It is:

$$P\ (psi) = 2.16x10\square \left[\frac{W^{1/3}\ (lbs)}{R\ (ft)} \right]^{1.13}$$

As we have seen before, the expression $W^{1/3}$ / R is simply the energy density. The coefficient before the bracket can be calculated from the energy density of the explosive and the efficiency of coupling its detonation energy to water. While it was obtained for TNT, it fits Pentolite and other high-energy explosives very well.

The next important scaling relation is the impulse, which has a similar form, except that the charge weight appears twice in it. That is, when the charge weight is increased, it increases the impulse approximately twice as fast (on a dB, or logarithmic, scale) as it increases the pressure. The relation is:

$$1\ psi \bullet sec) = 1.78\ W^{1/3}\ (lbs) \left[\frac{W^{1/3}\ (lbs)}{R\ \ (ft)} \right]^{0.94}$$

This is the quantity that is used to assess the potential for harm to marine animals from acoustic waves. Technically, it is necessary for *both* the pressure *and* the impulse to be above thresholds that depend on the particular animal and its size.

The third quantity for which general scaling laws have been published and widely used is the pulse width, the mean duration of the acoustic pulse. It is:

$$\tau\ (\mu\ sec) = 58\ W^{1/3}\ (lbs) \left[\underline{W^{1/3}\ (lbs)} \right]^{-0.22}$$

For this work, its principal value is in determining the effective wavelength of the pressure pulse. This determines the degree to which diffraction affects the wave when it is propagating in shallow water.

2.3 REFRACTION AND DIFFRACTION

In the ray theory of light (Rossi, 1957), refraction is related to the index of refraction of a medium, say glass. The index is defined as n = c/*v,* where c is the speed of light in vacuum, and *v* is the speed of light in the medium of index n. In acoustics, the relation depends upon both media. At a boundary between two fluids, the index of refraction is n = $\rho_1\ c_1\ /\ \rho_2\ c_2$, where the ρ's are the densities of the media, and the c's are the sound speeds. The products are the acoustic impedances.

Diffraction is most easily calculated by reference to the Cornu spiral (Rossi, 1957). It is a subject which is complex to explain, but relatively simple to compute. Basically, it is an additional dispersive refraction that is due to the finite size of the wavelength compared to other scale lengths, such as the water depth. The Cornu Spiral is a two-dimensional plot of two integrals that represent vector components of the wave propagating about an obstacle. The intensity of the diffracted wave is proportional to the distance between two points on a spiral, each of which is determined by a relation between location of a point on an observing surface for the wave, and the wavelength. Rossi and other authors relate the intensity on the observing surface to the diffraction of a plane wave incident on the obstacle. For our purposes, we invert the process, and determine the intensity of an outgoing plane wave from the diffracted (spherical) waves emanating from the pressure source in the observational plane. The Cornu spiral is illustrated on the following page.

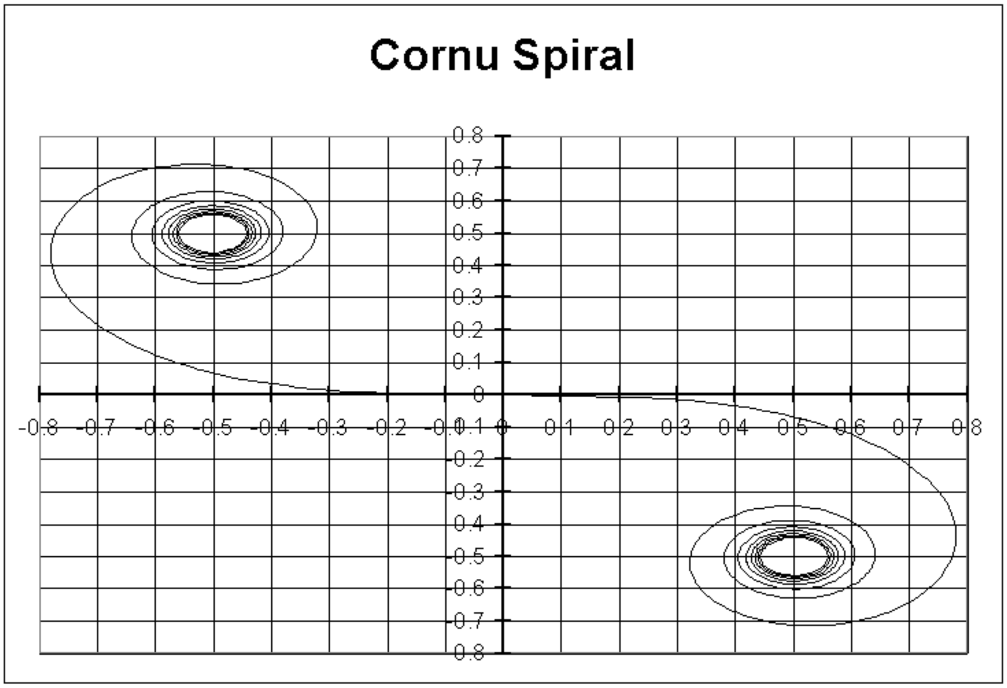

Figure 10. Cornu spiral